MODELLING OF THE PLASTICITY IN COLD COMPACTION OF METAL POWDERS

M. D. Riera, J. M. Prado

Centre Tecnològic de Manresa, Universitat Politècnica de Catalunya, Spain

ABSTRACT: Powder Metallurgical Industry is very interested in spreading its applications and improve the quality of the PM products. Therefore, a detailed knowledge of their processes, in order to control them, is necessary. Many different types of models have been used to represent the mechanical behaviour of these materials; however, nowadays, most of the groups working in this field admit that metallic powders and green compacts have to be considered as granular materials. Plasticity models specially defined for geological materials are being applied on metallic aggregates. Nevertheless, none of the known ones can represent adequately their mechanical behaviour, specially in states of failure.

KEYWORDS: Plasticity, Granular Materials, Compaction of Metal Powders, Modelling.

1. INTRODUCTION

Powder Metallurgy, as a metalworking process, unites to its undeniable technological interest, important savings of material and energy; this has promoted its acceptance in many different industrial sectors. Moreover, this arrives when the Society worries about the Ecology and the protection of the Environment. This technique does not generate smoke nor chemical contaminants. Most of the developed countries are conscious of the necessity to recycle the materials; they are exhaustible, more and more expensive resources and of difficult recovery. Nevertheless, metallic powders are very frequently manufactured from scraps; moreover, PM components require very few, or no, operations of machining (*net shape* and *near-net shape*) and, therefore, it generates minimum losses of matter.

Nevertheless, Powder Metallurgy presents restrictions; some of them are inevitable, depend on the own process and affect mainly the design of the piece; geometric requirements and those concerning the toughness limit the possibilities of this technology. Another type of limitations, also well stablished, are mostly associated to the compaction stage: friction between particles and tools induces a non-uniform density distribution in the compact. The heterogeneous state of stress developed produces very frequently cracks in the preform, especially during its ejection from the die, and the fracture of the tools.

All these problems have been traditionally solved by means of *trial and error* methods. However, the current development of new and more efficient tools of calculus reduces the cost of the design and manufacture processes and contributes to improve the quality of the product. In this respect, the main objective of the numerical simulation is to determine the optimal means to produce pieces without defects. In Metalworking, the design and the control need a deep knowledge of the mechanics of the deformation during the process; the influence of variables such as geometry, friction and properties of the materials must be well established to define properly the tools and their kinematics, the parameters of the process and to predict and prevent the appearance of defects. Computer simulation has become one of the most interesting technique in the modern metalworking Industry; however, its success depends mainly on the model applied to represent the behaviour of the material. Differently to most of the conventional materials, the mechanical behaviour of these aggregates of particles is not yet well known. Not many time ago the sintering stage of the PM technique seemed to be the one responsible for all the properties of the final component. Recently, a part of the interest has been centred on the compaction and metallic powders are already treated as granular materials. Nevertheless there is no a generally accepted theoretical body to explain the mechanical behaviour of the particles during their cold compaction; there is no a general agreement about the plastic model and the elasticity has been practically ignored.

In this paper the authors pretend to present the different type of models currently envisaged in this field and giving information at different levels; all of them are useful to understand the behaviour of these materials.

Consolidation of a metallic powder begins by filling and transferring the powder into the compaction die. This stage, currently under study, is characterised by the density distribution of the mass of loose powder and depends not only on the nature of the particles but, also, on the methods of filling and transference into the die. Several models, based on different theories, are being published [1,2,3]. After filling the mould, the powder is compressed to produce a metallic aggregate. This procedure has been qualitatively described by Seeling and Wulf [4] who defined three stages during the compression. In the first one, corresponding to the lowest level of applied pressure, particles rearrange. The second part involves elastic and plastic deformation of particles throughout their contact areas. These two phenomena, sliding and deformation, can occur concurrently from the beginning of the compression, as stated Fishmeister, Arzt and Olsson [5]. Moreover, metallic particles strain harden; two types of hardening act: that corresponding to particles and the geometrical one, due to the progressive increase of the contact areas between these particles. Therefore, in the last stage, for high stresses, the only mechanism governing the densification is the elastic deformation.

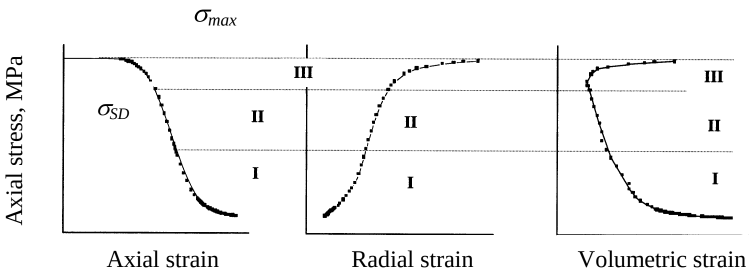

Fig. 1: Evolution of the components of the strain during an uniaxial compression test, after [9].

The powder compact is, therefore, a packing of deformed particles, which are able to move with regard to each other; it exhibits the main features characterising a granular material: interparticle porosity and sliding of these particles throughout their contacts. A remarkable feature is its dilatation under uniaxial compression, which has been shown for geological materials [6] and, more recently, for green powder compacts [7, 8]. Figure 1 presents the results corresponding to a simple compression test applied on a green ferrous compact. During the test, the evolution of the components of the strain define three parts: at the beginning of the compression (I), the curves show an initial *foot* corresponding to a transitory plastic behaviour which can be related to some internal friction phenomena. With further deformation, the stress grows quickly with strain (II), which has an important elastic component. And a final stage (III) where a saturation stress, σ_{max}, is reached. The specimen fails during this last region. Nevertheless, before the failure and just at the beginning of this third stage, the compact starts its dilatation (at σ_{SD}); the aggregate expands, instead of densifying as a porous material (a sintered compact, for instance).

At the present two main type of models are being used to study and represent the mechanical behaviour: Micromechanical models and those based on the Continuum Mechanics.

2. MICROMECANICAL MODELLING

The interest of developing microstructural models is due to the fact that describing the behaviour of the material at the microstructural level can lead to a better understanding of the mechanisms acting during the compaction. The information about the physical phenomena of the process may be crucial to define a constitutive law. When analysing the compaction process from a micromechanics point of view, different approaches can be distinguished. The first one consists on studying the pore structure and its evolution during the applied loading path; the alternative analysis is based on a particle arrangement.

The first theoretical model, in strict sense, applied to study the compression of metallic particles was defined by Torre [10]. He assumed that the pores in the green compact could be represented by a single large pore in the centre of a hollow rigid, perfectly plastic sphere. By applying the Tresca' yielding criterion he calculated the pore volume as a function of the hydrostatic pressure applied. Heckel [11], Bockstiegel [12], Klar, Hewitt, Wallace and de Malherbe [13] have also investigated this process and defined revisions to the Torre' s model. Green [14] and Garson [15] applied the theory of Plasticity to a model also based on the change in the pore structure.

Sundström and Fischmeister [16] emphasised on the difficulty to extend the one-pore model to a system multi-pore and studied the compression of a concave pore defined by four particles; they solved the behaviour of this unit by means of the finite element method (Fig. 2). This model shows good agreement with experimental results at high densities of the compact although it incorporates the geometrical hardening of the system.

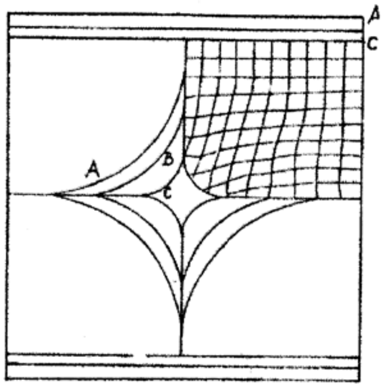

Fig. 2: Bidimensional model studied by Sundström and Fischmeister [16]. Change in the pore structure for different level of porosity: A=13.7%, B=7.3%, C=1.6%.

Further progress regarding detailed mechanisms is mainly based on the evolution of arrays of particles in contact. After the first works, involving only two spheres (Morrison and Richmond [17], Kakar and Chaklader [18], ...), the more interesting ones suppose regular or random arrangement of monosized particles submitted to different states of stress. The assumption of regularly packed particles simplifies the analysis. In practical situations, however, the random arrangement is most likely to occur, as demonstrated Scott [19] and Mason [20]. Fischmeister, Artz and Olsson [21] stated that the relative movement among particles is limited to an initial stage of the densification process; as the applied pressure increases, ductile particles deform and work hardens; the contacts between them vary, in intensity and in number. These authors found experimentally that the average number of contacts (*coordination number*) per particle increased almost linearly with the compaction pressure.

Artz [22] suggested the use of an average Voronoi cell. As depicted in Fig. 3, it consists on a polyhedron containing one powder particle where the number of faces of adjacent cells is determined by the number of nearest neighbours for the particle in question. During the compaction, the particles grow in an imaginary way around fixed centres with constant volume of the preform retained. Artz characterise the shape of this cell and its evolution by means of the *Radial density function* (RDF) given by Scott [19] and Mason [20]. He derived relationships between the shape of the contacts and the density of the aggregate. However this study is valid only for perfectly plastic materials. *A posteriori*, Fischmeister and Artz [23] incorporated the effect of the strain and the geometrical hardening. An scheme of this model is shown in Fig. 4.

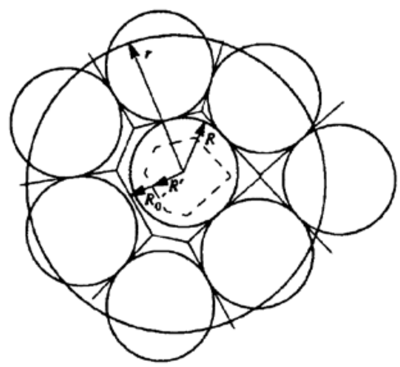

Fig. 3: Bidemensional scheme of the Voronoi cell, after [21].

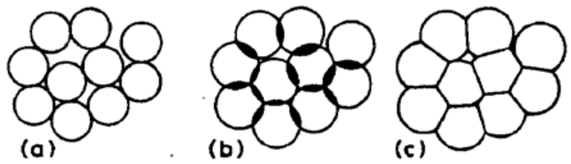

Fig. 4: Model of Fischmeister and Artz: a) the particles grow around fixed centres; b) part of the material is extruded to the voids; c) the value of the RDF determines the current number of coordination. After [23].

Other researches adopted this type of treatment. Among them, the work done by Helle, Easterling and Ashby [24] should be mentioned. They defined a macroscopic yielding function throughout a simpler mathematical treatment, valid for purely hydrostatic states of stress. McMeeking [25], Xu and McMeeking [26] and Fleck, Kuhn and McMeeking [27] found a more general function which also take into account shear stresses. Fig. 5 represents the model analysed by these authors and a detail of the stresses in the contact between two spherical particles.

Ogbonna and Fleck [28], stated that the yielding behaviour of a particle aggregate depends not only on its density, but also on the applied loading path. Fig. 6 shows the yield loci corresponding to two different states described by these authors.

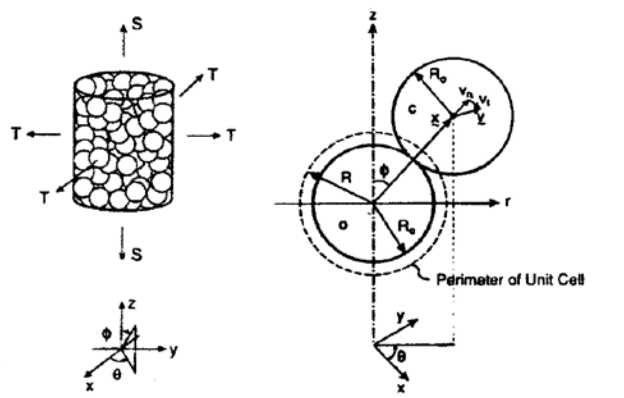

Fig. 5: Macroscopic element corresponding to the model by Fleck, Kuhn and McMeeking and detail of the contact between particles. [27].

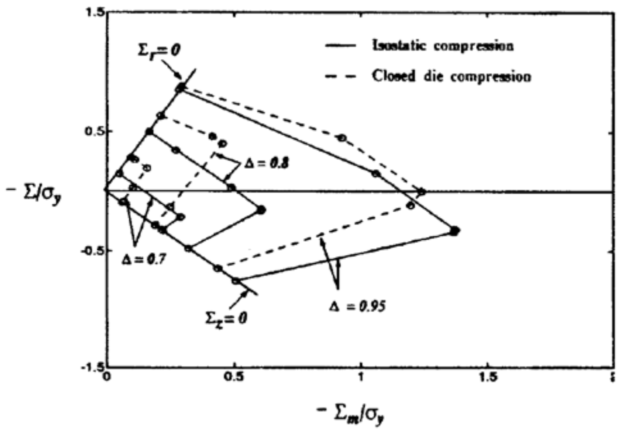

Fig. 6: Yield loci obtained by means of isostatic compression and die compression. [28].

This field continues giving very interesting information about the compaction of arrangement of particles. As Molerus stated in a very interesting paper about cohesive powders, *"From the practical as well as from the scientific point of view, it should be useful to search for a connection between the continuum mechanics aproach and the particles approach, in order to arrive at a deeper insight into the behaviour of cohesive powders"* [29]. The authors of the present paper participate of this idea.

3. CONTINUUM MODELLING

Cold compaction of metallic powders has been studied from a more theoretical point of view: the consolidation, as a time independent plastic flow process, has been represented by means of groups of yield surfaces dependent on the relative density, *R*, and on the invariants of the stress. The yielding of not fully dense materials is more complicated than that presented by the bulk material; in the former case the mechanical behaviour usually involves changes of volume; in this situation the yielding phenomenon is determined not only by the deviatoric component of the stress, but, also, by the hydrostatic pressure. Therefore, many researches defined models of Plasticity based on modifying the von Mises' yielding criterion in order to include the effect of the hydrostatic component [30].

Most of these yield models generate elliptical yield surfaces which predict the same behaviour in tension and in compression (Fig. 7).

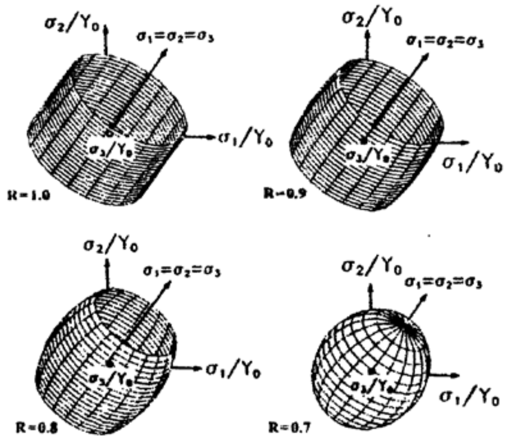

Fig. 7: Yield surfaces calculated using the following equation: $AJ_{2D} + BJ_1^2 = Y_R^2 = \eta Y_o^2$ (A, B and η are parameters dependent on the density of the material; J_{2D} and J_1 are the second invariant of the deviatoric stress and the first invariant of the stress tensor, respectively; Y_R and Y_o are the yield stress of the material with a relative density of R and the yield stress of bulk material, respetively. After Lee and Kim [31].

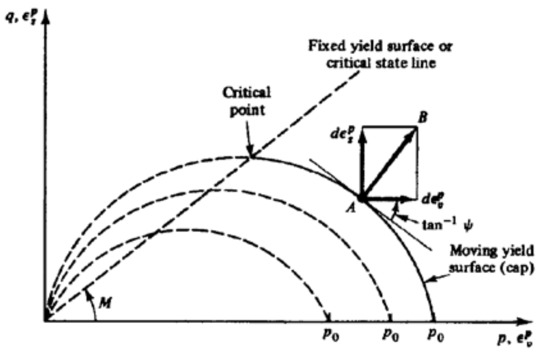

Fig. 8: Modified CAM-clay Plasticity model. [33].

The models proposed by Green [14] and Gurson [15] are the most important and well known, specially the second one. In general, this type of Plasticity laws are useful to model the mechanical behaviour of porous metals.

Roscoe and his co-workers [32] showed that a group of steel balls submitted to different loading paths, behave like a granular material, a cohesionless material; then, the type of models defined specifically for geological materials can be successfully applied to represent the mechanical behaviour of aggregates of metallic particles. They defined the concept of *critical state* and, based on it, these researches stated the *CAM-clay* Plasticity, developed for clays in the fifties and used recently to represent the cold compression of metal and ceramic powders. Fig. 8 shows the yield surfaces in the space of the hydrostatic and deviatoric stresses corresponding to the modified CAM-clay model.

These models are substantially different from the quadratic, symmetric yield surfaces previously defined: they take into account the limited cohesion between particles; hence, the tensile strength of these materials is much lower than their strength in states of compression. Among this group of Plasticity models, the Drucker-Prager/CAP one is currently the most frequently used to represent the mechanics in the powder compaction process. It seems to be appropriate, especially in the consolidation region. Nevertheless, the authors of the present paper have some doubts about its effectiveness in representing its performance in states of failure.

Drucker and Prager [34] proposed a failure criterion that consists of a straight line, the failure line, the failure surface (Fig. 9), in the space of the first and second invariants of the stress and deviatoric stress tensors, J_1 and J_{2D}, respectively. But they realized that most of the materials that they were studying showed plastic strain from the first stages of the loading process; therefore, during the loading path, *L-L'* in Fig.9, the material is yielding constinuously up to the failure, or ultimate state, which can be considered as the last yield surface; moreover, during the successive yielding the material hardens. This behaviour can be represented by means of a series of yield surfaces, the hardening caps, previous to the failure. This idea was first proposed by Drucker, Gibson and Henkel [35] and represented as it is shown in Fig. 10. For simplicity these authors supposed that the caps were of circular shape, but it depends on the material and it can be experimentally determined. The CAP model [36] initially used to simulated the plastic behaviour of geological materials, has also been shown as very adequated in the case of metal powder compaction.

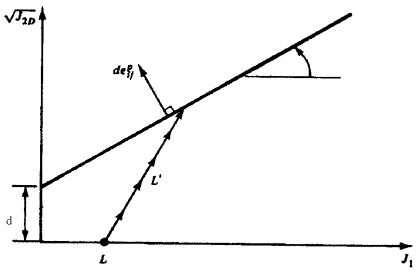

Fig. 9: Drucker-Prager criterion. $d\varepsilon^{p}_{ij}$ is an increment of the plastic strain and d and β are parameters of the material. The line *L-L'* corresponds to a loading path. After [33].

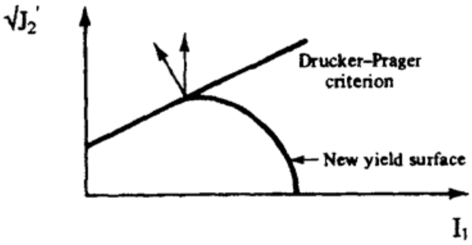

Fig. 10: Mechanical behaviour of strain hardening granular materials, after [33].

The original model uses two yield surface segments: a pressure dependent Drucker-Prager shear failure surface and a compression cap yield surface. The failure surface is perfectly plastic in the sense that no mechanical strain hardening occurs, but plastic flow on this surface produces inelastic volume increase; in other words, for states of stress on this surface the sample dilates under constant applied stress. The equation describing this failure surface is the following:

$$f_1 = q - p\tan\beta - d = 0 \qquad (1)$$

q and p are the deviatoric and the hydrostatic stresses, respectively; β, is the angle of friction, and d, the cohesion of the material. The shape of this surface in the *p-q* plane is, then, a straight line

The cap yield surface has an elliptical shape in the *p-q* plane and hardens (expands) or softens (contracts) as a function of the volumetric plastic strain: volumetric plastic compaction (yielding on the cap) causes hardening, while volumetric plastic dilatation (yielding on the shear failure surface) causes softening. The equation describing the cap yield surface is:

$$f_2 = [(p-p_a)^2 + (Rq)^2]^{1/2} - R(d + p_a \tan\beta) \qquad (2)$$

p_o is an evolution parameter related to the hydrostatic compression yield stress, p_b, which represents the volumetric hardening or softening, and R is a material parameter that controls the shape of the cap. All these features are shown in Fig. 11.

Nevertheless, the results presented in Fig. 1 suggest that a certain number of modifications should be introduced in this latter model in order to represent the plastic behaviour of metal powder. The successive states of stress existing in a compact during an uniaxial compression test are represented in the *p-q* space by means of a straight line of slope 3 and passing through the origin. The fact that during the compression the sample dilates means that the compression loading path cuts the Drucker-Prager line when the increase in volume begins; but, opposed to the behaviour of geological materials, dilatation only continues under progressively greater applied stresses. Therefore, the Drucker-Prager line changes during this dilatation stage. This is reflected in equation (1) by a decrease of the material cohesion, d, and an increase in the friction angle, β. The dilatation of the sample takes place, as it has been already stated, through an increase in the distance between the centres of neighbouring particles; this gives rise to a higher volume fraction of porosity and a lower material cohesion. The hardening of the surfaces of contact between particles increases the internal friction in the sample and, consequently, the friction angle. The uniaxial compression test dos not give direct information about the evolution of the cap yield surface during this type of plastic deformation, but the fact that particles have hardened should produce an

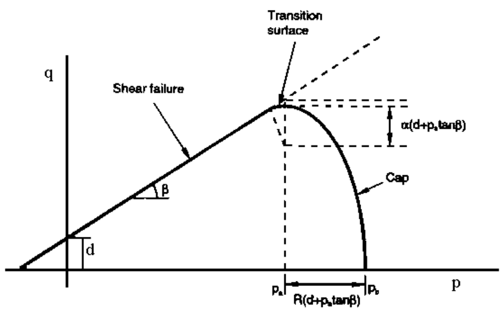

Fig. 11: Yield surfaces for the Drucker-Prager/CAP model in the space of hydrostatic, *p*,-deviatoric, *q*, stresses, with a transition region. After [37].

expansion of the cap surface. In order to check the correctness of this latter suggestion triaxial compression tests on previously uniaxially compressed samples should be performed. Fig. 12 shows the expected yield surfaces of a sample before and after an uniaxial compression test, stopped before failure. Hence, the new yield surface has expanded, except in the vicinity of the tensile p axis, in spite of the fact that the density of the sample has decreased; this is an important difference with respect to the case of geological materials. This particular behaviour is the consequence of the mechanical hardening capacity of the metal powder particles. In order to reflect the observed behaviour of metal powder compacts, the parameters p_a and β in previous equations (1) and (2) should be adequately modified. In geological materials, due to the ceramic nature of their particles, hardening is the result only of volume decrease; in metal powders, the plastic deformation of the particles has to be considered as a new mechanism of sample hardening. Hence, the parameters p_a and β should be dependent not only on sample density but, also, on particle hardening.

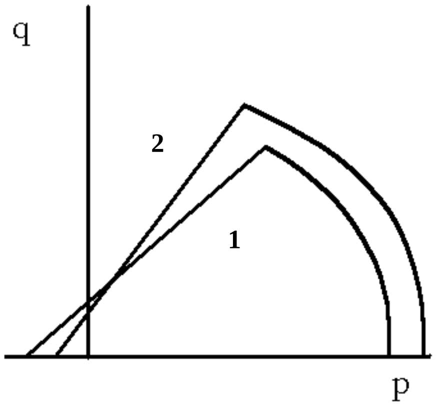

Fig. 12: Expected yield surfaces of a sample before (1) and after (2) an uniaxial compression test, stopped before failure.

REFERENCES

1. Editors Anita Mehta. "Granular matter. An interdisciplinary approach". Ed. Springer-Verlag. New York. 1994.
2. Patrice Porion. "Internal friction and avalanches in the granular materials". *PhD Thesis*. Université de Lille. 1994.
3. Lyndon Smith. "Monte Carlo Simulation of particle behaviour". *Metal Powder Report.* Vol. 56. Nº 1. Pp. 32-35. 2001.
4. Seeling, P.R. and Wulff, J. "The Pressing Operation in the Fabrication of Articles by Powder Metallurgy". *Trans AIME*. Vol. 166. Pg. 492-500. 1946
5. Fischmeister, H.F.; Arzt, E. and Olsson, L.R. "Particle Deformation and Sliding During Compaction of Spherical Powders: A Study by Quantitative Metallography". *Powder Metallurgy*. Vol. 21. Pg. 178. 1978.
6. Schofield, A. and Wroth, P. *Critical State Soil Mechanics*. Editado por McGraw-Hill. London. 1968.
7. M. D. Riera and J. M. Prado. "Uniaxial Compression Tests on Powder Metallurgical Compacts". *Proceedings of the 1998 Powder Metallurgy World Congress & Exhibition.* CD-Document number 615. Ed. EPMA. UK. 1998.
8. Mosbah, P., Bouvard, D., Laniel, J., Ouedraogo, E. andy Stutz, P. "Rheological characterization of metal powder following various loading paths". *Powder Metallurgy World Congress. PM' 94*. Les Éditions de Physique. Pg. 677. París. 1994.
9. M. D. Riera. "Comportamiento mecánico de compactos pulvimetalúrgicos". *Thesis.*Universidad Politécnica de Cataluña. 1999.
10. Torre, C. "Theory and Behaviour of Pressed Powders". *Berg-und Hüttenmännische. Montan*. Hochschule Leoben. Vol. 93. Pg. 62. 1948.
11. Heckel, R.W. "An Analysis of Powder Compaction Phenomena". *Trans. AIME*. Vol. 221. Pg. 1001. 1961.
12. Bockstiegel, G. "The Porosity-Pressure Curve and its Relation to the Pore Size Distribution in Iron Powder Compacts". *Modern Developments in Powder Metallurgy*. Pg. 155. Vol. 1. Hausner. H.H. Ed. Plenum Press. New York. 1966.
13. Hewitt, R.L., Wallace, W. and de Malherbe, M.C. "The effects of strain hardening in Powder Compaction". *Powder Metallurgy*. Vol. 16. No. 31. Pg. 88-106. 1973.

14. Green, R.J. "A Plasticity Theory for Porous Solids". *Int. J. of Mechanical Science*. Vol. 14. Pg. 215. 1972.
15. Gurson, A.L. "Continuum Theory of Ductile Rupture by Void Nucleation and Growth: Part I-Yield Criteria and Flow Rules for Porous Ductile Media". *Journal of Engineering Materials and Technology*. Paper No. 76-Mat-CC. 1976.
16. Sundström, B. and Fischmeister, H.F. *Modern Developments in Powder Metallurgy*. Editado por H.H. Hausner y W.E. Smith. Vol. 6. MPIF. Princeton, N.J. USA. Pg. 203. 1974.
17. Morrison, H.L., Richmond, O. and M.L. Devenpeck. "Sphere indentation with application to the Brinell hardness test". *Int. J. Mech Sci.* Vol. 16. Pg. 75-82. 1974.
18. Kakar, A.K. and Cchaklader, A.C.D. "Deformation Theory of Hot-Pressing". *Journal of Applied Physics*. Vol. 38. Pg. 3223. 1967.
19. Scott, G.D. "Radial distribution of the random close packing of equal spheres". *Nature*. Vol. 194. Pg. 956. 1962.
20. Mason, J. and Bernal, J.D. "Co-ordination of randomly packed spheres". *Nature.* Vol. 188. Pg. 910. 1960.
21. Fischmeister, H.F., Arzt, E. and Olsson, L.R. "Particle Deformation and Sliding During Compaction of Spherical Powders: A Study by Quantitative Metallography". *Powder Metallurgy*. Vol. 21. Pg. 178. 1978.
22. Arzt, E. "The influence of an increasing particle coordination on the densification of spherical powders". *Acta Metallurgica*. Vol. 30. Pg. 1883. 1982.
23. Fischmeister, H.F. and Arzt, E. "Densification of powders by particle deformation". *Powder Metallurgy*. Vol. 26. No. 2. Pg. 82. 1983.
24. Helle, H.S., Easterling, K.E. and Ashby, M.F. "Hot-isostatic pressing diagrams: new developments". *Acta Metallurgica*. Vol. 33. Pg. 2163. 1985.
25. McMeeking, R.M. "The analysis of shape during isostatic pressing". *Int. J. Mech. Sci. Vol*. 34. No.1. Pg. 53-62. 1992.
26. Xu, J. and McMeeking, R.M. "An analysis of the can effect in an isostatic pressing of copper powder". *Int. J. Mech. Sci*. Vol. 34. No.2. Pg. 167-174. 1992.
27. Fleck, N.A., Kuhn, L.T. and McMeeking, R.M. "Yielding of metal powder bonded by isolated contacts". *J. Mech. Phys. Solids*. Vol. 40. No. 5. pG. 1139. 1992.
28. Ogbonna, N. and Fleck, N.A. *Acta Metallurgica et Materialia*. Vol. 43. No. 2. Pg. 603. 1995.
29. Molerus, O. "Theory of Yield of Cohesive Powders". *Powder Technology*. No. 12. Pg. 259-275. 1975.
30. Doraivelu, S.M., Gegel, H.L., Gunasekera, J.S., Malas, J.C., Morgan, J.T. and Thomas, J.F. Jr. "A new yield function for compressible P/M materials". *Int. J. Mech. Sci*. Vol. 26. No. 9/10. Pg. 527. 1984.
31. Lee, D.N. and Kim, H.S. "Plastic Yield Behaviour of Porous Metals". *Powder Metallurgy*. Vol. 35. No. 4. 1992.
32. Roscoe, K.H., Schofield, A.N. and Wroth, C.P. "On the Yielding of Soils". *Géotechnique.* Vol. 8. Pg. 22-53. 1958.
33. Desai, C.S. and Siriwardane, H.J. *Constitutive Laws for Engineering Materials with emphasis on Geologic Materials*. Editado por Prentice Hall, Inc. Englewood Cliffs, N.J. USA. 1984.
34. Drucker, D.C. and Prager, W. "Soil Mechanics and Plastic Analysis of Limit Design. *Quarterly of Applied Mathematics.* Vol. 10. Pg. 157-175. 1952.
35. Drucker, D.C., Gibson, R.E. and Henkel, D.J. Soil Mechanics and Work Hardening Theories of Plasticity". *Proc. ASCE*. Vol. 81. Paper 798. Set. 1955.
36. Sandler, I., Dimaggio, F.L. and Baladi, Y. "Generalized Cap Model for Geological Materials". *Journal of Geotechnical Engineering Division*. Vol. 102. No. GT7. Pg. 683-699. 1976.
37. Hibbitt, Karlsson and Sorensen, Inc. *ABAQUS Theory Manual. Version 5.7.* 1997.